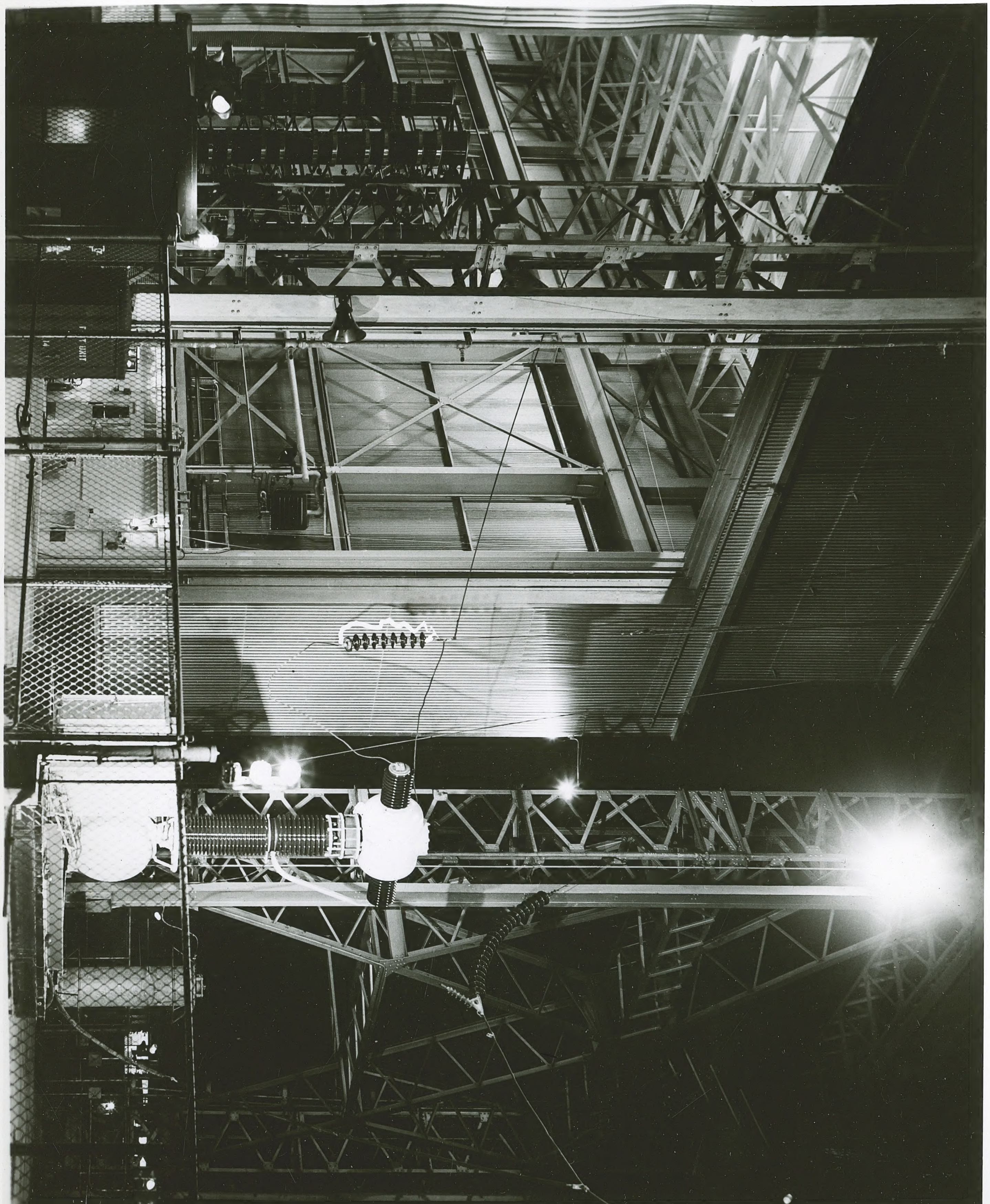

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INSULATION COORDINATION OF CIRCUIT BREAKERS DURING OPERATION

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INTRODUCTION

Industry standards specify that a circuit breaker must withstand a certain value of 60 cycle high potential test voltage and a higher value of impulse test voltage when it is in the static state and contains clean oil. During and following interruption, large volumes of gas bubbles are exhausted from the interrupter and are distributed within the bulk oil between the interrupters and the tank wall. Little has been known and published concerning dielectric strengths during this vital period.

A circuit breaker may be subjected to transient voltages from either the source side or the line side during interruption. Industry standards do not designate what the performance of breakers should be on such transients.

Use of special circuits has permitted testing circuit breakers up to full interrupting current and, following interruption by various intervals, injecting switching surge voltages. These surges have also been used to simulate multiple lightning voltages.

One of the most unexpected of the results is that there is a drop of impulse dielectric strength in the typical dead-tank oil circuit breaker a few cycles after interruption to the order of 50% of its basic impulse level. Viewed from the source side, the problem is to keep the dielectric strength to ground higher than the power frequency recovery voltage, its recovery transient voltage, and other transient voltages that might appear on the source side due to simultaneous interruption by adjacent breakers. Several solutions to the problem are possible. In the highest power oil circuit breakers, dielectric strength after interruption has been increased by more than 50% by installation of closed cell sponge rubber pads on the tank walls. This yields substantial margin over requirements.

Viewed from the transmission line side, the results of lightning voltages across the circuit breaker are, of course, the prime consideration.

Circuit breakers are usually designed to have a basic impulse level about equal to or slightly lower than the flashover voltage of the transmission line to which they are connected. During lightning-initiated fault operations, multiple lightning voltages often appear on the line. These will travel to the open breaker and tend to double in voltage because of reflection. If the wave fronts are assumed to be very steep, rod gaps which are frequently used across the breakers set to a nominal percentage above the BIL will not flash over quickly enough to reduce materially the crest voltage.

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One of the purposes of this paper is to introduce new data and review the available information and concepts in an attempt to determine whether circuit breakers should be designed on a static basis to withstand these double voltages that might conceivably appear, or on the contrary whether there are some practical mitigating circumstances that prevent these voltages from appearing or causing damage in a significant number of cases. It is found that in spite of the presence of the low dielectric strength sparkover path from line interrupter to ground after interruption, the incidence of power faults and damage along this path is practically zero. Two design principles involving coordination of self healing paths within the breaker are presented which aid in preventing internal power failures.

Oil Circuit Breakers: Design to Withstand Source Side Switching Surges

The problem of providing adequate margin in dielectric strength after interruption to insure against internal flashover to tank by a switching surge on the source or bus side will now be considered. The problem is particularly pronounced in those high-capacity breakers intended for application only on effectively grounded systems (230 kv and above) where the ratio of the rated BIL and rated low frequency withstand test voltage to the operating voltage is relatively low.

The importance of the problem is illustrated in the plot of the data (Fig. 1) of 60 cycle dielectric strength to tank following interruption of short circuit currents. These data, taken on a typical high voltage high-capacity dead-tank oil circuit breaker, are plotted in percent of the rated low frequency withstand test voltage which the breaker passes without difficulty in the static condition. The dotted line represents the approximate boundary between breakdowns and withstands as influenced by the current interrupted. From this plot it is apparent that the 60 cycle dielectric strength drops to approximately fifty percent shortly after interruption of 15,000 amperes, and to approximately thirty-three percent after interruption of 35,000 amperes. Various interrupter types tried had little effect on the results.

For breakers intended for effectively grounded neutral application and rated in excess of approximately 25,000 interrupting amperes, there is negligible margin for switching surges following interruption of a fault near rating. Because this situation can lead to rather disastrous internal flashovers to tank from the interrupter energized by the bus, a program was initiated in the Company with which the authors are associated to develop means for substantially increasing this dielectric strength after interruption in high-capacity breakers.

A. Analysis of Lowered Dielectric Strength After Interruption

From the data previously mentioned it was determined that the period of weakest dielectric strength following a short circuit interruption was 3 to 5 cycles after arc extinction in the interrupters. It is significant that this time interval after interruption coincides with a minimum transient pressure swing in the bulk oil of the tank to a value in the order of 13 psi below the static equilibrium value. A typical tank

pressure record is shown in Fig. 2 and is characteristic of dead-tank oil circuit breakers, differing among designs primarily by the period of the oscillation. The phenomena responsible for this transient pressure in the tank together with the mechanism by which the dielectric strength is lowered in relation to its negative swing can be postulated as follows: The interruption process in an oil interrupter is effected by the arc decomposition of oil in the interrupter to gaseous products, largely hydrogen, which in turn is ejected from the interrupter exhaust ports at substantial pressure. It is this gaseous blast that provides the major interrupting effort. The amount of gas generated during an interruption corresponds approximately to that of 100 cubic centimeters of gas at standard temperature and pressure per kilowatt second of arc energy. Because the greatest rate of arc energy release is at the longest portion of the stroke, just prior to interruption, we can expect at this time a rather fast build-up in the quantity of gas, and hence pressure, in a gas bubble in the bulk oil of the tank just outside the interrupter. The subsequent sequence of events is then not unlike those that would occur if a pressurized container of gas in the bulk oil of the tank were suddenly burst and the gas allowed to expand by the movement of oil away from the region and up into the relatively large volume of air above the oil line in the tank. The energy expended by the expanding gas bubble imparts a substantial kinetic energy to the oil, continually increasing the oil flow rate until the gas bubble pressure is reduced to approximately that of the atmospheric pressure in the air volume above the oil level. At this instant the forces on the oil column are essentially balanced but the oil continues to move upward because of its kinetic energy. This upward motion of the oil and expansion of the gas bubble continues then until the kinetic energy is expended in the work of expanding the gas bubble below atmospheric pressure. At this instant, 3 to 5 cycles after interruption, the bubble pressure is at its minimum value, about -13 psi, and the unbalanced forces on the oil column initiate a reversal in the oil flow toward the low pressure bubble. The second positive peak in the tank pressure record occurs when the oil kinetic energy again causes overshoot of the eventual equilibrium pressure in the opposite direction. This negative swing in bubble pressure, about 3 to 5 cycles after interruption, has two deleterious effects on dielectric strength to tank. First, the bubble expands in volume tremendously and consequently extends further toward the tank wall. Second, the dielectric strength of the gas bubble decreases as its pressure decreases. The net result is a large reduction in dielectric strength, this reduction increasing with the volume of gas exhausted and hence with the amount of the current interrupted.

B. Method of Improving Dielectric Strength to Tank After Interruption

With a physical picture of the phenomena associated with the lowering of the dielectric strength, several approaches to an improvement are possible. One approach is to reduce the volume of the air enclosed at the top of the tank to the point where the eventual equilibrium pressure after interruption is considerably higher than atmospheric pressure as a result of the gas evolved during arcing. The resulting oscillatory transient would thus be about a higher equilibrium value, and the minimum bubble pressure therefore substantially higher. The construction of the lenticular tank 138 kv oil circuit breaker is one example of the use of this approach. Fig. 3 shows the limited volume in the bushing pockets in which the oil level line is maintained.

Another possible approach is that of sealing and maintaining a pressurized atmosphere in the tank. Such an approach, however, detracts from the simplicity of oil circuit breaker structures, with substantially increased maintenance problems.

A second solution adopted by the Company with which the authors are associated, and which has been incorporated in all high-capacity oil breakers rated 230 kv and 345 kv is that of installing pressure control pads over a portion of the inner walls of the tank as mentioned in a previous paper[1]. These pads are one inch thick and are of closed-cell Buna-N sponge. Each individual cell is nitrogen-filled and sealed from the other cells by the Buna-N. The pads, therefore, absorb no oil except at the edges where the cells are cut.

The presence of these pressure control pads effects an increase in dielectric strength after interruption by reducing the negative swing of the pressure transient in the tank. Furthermore, this beneficial effect is attained without the necessity of reducing any relatively large air volume at the top of the tank. Functioning of these pads in the desired manner is dependent upon two requirements. First, the surface area of the rubber pads must be several times larger than the access area to the large-volume air cushion above the oil level line in the tank. This requirement is easily achieved in the lenticular tank designs of the Company with which the authors are associated because the oil level line is within the bushing pockets, which are of much smaller diameter than the tank itself. Second, the volume of the rubber pads must be in the order of the largest volume of gas generated during interruption, referred to atmospheric pressure. With the realization of these requirements, these pads

serve as a large-area, limited-volume cushion which limits the negative pressure swing in the exhaust gas bubble in the following manner: when the gas is expelled from the interrupter, oil can move away spherically in all directions rather than just up toward the air space. The effective mass of the oil to move out of the way is, therefore, materially reduced and the initial peak bubble pressure somewhat lower. More important, however, is the fact that the surface area of the rubber is much larger than the entrance area to the air volume at the top of the tank (about 10 to 1). Consequently, only a small part of the moving oil goes toward the large air volume and most is accelerated toward the rubber cushion at the tank walls. The rubber cushion has a compression characteristic similar to an air pocket; however, unlike the air volume at the top of the tank, it has a limited volume and as soon as the oil compresses it a little way it exerts an opposing force on the oil, enabling the accelerated oil to be stopped and reversed before the gas bubbles have expanded appreciably.

Looking at the operation in a different manner, the oscillatory motion of the oil is now principally between the initially pressurized exhaust gas bubbles and the tank wall cushion because of its much larger area as compared to the oil-air interface at the top of the tank. Because of the much smaller volume of the tank wall cushion the pressure transient excursions are greatly reduced and the oil-air interface at the top of the tank serves as leakage damping of the oscillatory pressure transient. The net result is that the exhaust gas bubble pressure is neither so high initially nor as low at its minimum value. The improvement in dielectric strength realized by this approach is illustrated in Fig. 4 in which all of the tests resulted in withstands. The dotted line on the plot is that of Fig. 1 and represents the dielectric strength for the same breaker under the same test conditions before installation of the rubber pads. It will be noted that the dielectric strength after interruption of the higher short circuit currents has been increased by a factor in the order of 2 to 1.

C. Effect of Reclosing Duty Cycles on Dielectric Strength to Tank

Additional data accumulated on dielectric strength to tank after multiple interruptions of 4-operation reclosing duty cycles, with the pressure control pads installed, demonstrated a lowering of dielectric strength with successive operations of the duty cycle. The duty cycle employed on these tests consisted of one high speed reclosure followed by two close-open operations delayed by 10 seconds and 30 seconds (0 + 0 Sec. + CO + 10 Sec. + CO + 30 Sec. + CO). Whereas no breakdowns occurred at the highest test voltage on the first or second operations,

(65% of the rated low frequency withstand test voltage) the dielectric strength for the third and fourth operations was reduced to approximately 55% and 48% of the rated low frequency withstand test voltage respectively, at interruption currents of 30,000 amperes.

In addition to the reduction of dielectric strength after the successive operations of a duty cycle, these data further demonstrate that the reduction in dielectric strength to tank caused by a fault interruption persists to a significant degree for many seconds after the interruption. The large gas bubbles exhausted by the interruption have floated up out of the oil into the air volume at the top of the tank in the relatively long intervals preceding the third and fourth operations resulting in the recovery of a substantial portion of the static dielectric strength to tank prior to the next operation. On the other hand, very small bubbles can be dispersed throughout the bulk oil of the tank for very long periods. This dispersion of very small gas bubbles very likely results, to a substantial degree, from the coming out of solution of dissolved gases in the oil during the pressure oscillation following interruption. Dielectric strength of oil containing finely dispersed gas bubbles is known, by hipot tests shortly after filling a circuit breaker, to be substantially below that value ultimately attained after standing for some time after filling. It can be concluded, therefore, that even with the reduction in tank pressure oscillation afforded by the pressure control pads and their substantial improvement in dielectric strength during the most critical period after interruption, the dielectric strength after interruption is significantly impaired for at least thirty seconds after a fault interruption.

However, the test data and field experience indicate that with either of the two solutions covered, the dielectric strength to ground is maintained sufficiently high to withstand source side transient voltages.

The pressure control pads are especially beneficial during repeated high power interruptions, such as encountered in high-capacity Industry standard reclosing duty cycles.

Oil Circuit Breakers: Design to Perform in Presence of Multiple Lightning Voltages

At the present state of the art it does not seem possible to design a circuit breaker that will never fail under a sufficiently improbable combination of events. One example would be the case of several successive multiple lightning voltages preventing a breaker from clearing on several successive half cycles of arcing. However, the problem from an Industry-wide point of view is to prevent occurrence of a significant number of failures, but at the

same time to avoid building added costly safety factors into breakers to withstand hypothetical conditions which actually would not cause significant maintenance expense. Such an approach necessarily involves estimates of probabilities and a certain degree of reasonable, calculated risk. Considering only the speculation that we might have voltages as high as 200% BIL during opening when the dielectric strength is only 50% of BIL, one would conclude that disastrous failure should be common. Actually the number of cases of power failure and damage from the line side interrupter through the low dielectric strength gas bubbles to ground is, in the authors' experience, so small as to be negligible. It is obvious that some important additional mitigating factors are acting. The following paragraphs attempt to throw light on some of them.

Impulse Dielectric Strength After Interruption

The data on dielectric strength after interruption plotted in Figs. 1 and 4 were obtained by application of 60 cycle voltage. In order to illustrate the dielectric strength characteristics on a basis more typical of lightning surges, these data are replotted in Fig. 5 in terms of percent of rated BIL and with the crest values of the actual 60 cycle test voltages multiplied by the factor 1.6. The factor 1.6 is the approximate factor by which rod gap sparkover voltage in air for a 3 microsecond chopped wave exceeds the sparkover voltage for 60 cycle crest, and was used in the absence of any more precise information as to the ratio of chopped wave impulse strength to 60 cycle strength of the gas bubbles in the tank. Even at relatively low values of fault current the impulse dielectric strength is only a fraction of the rated BIL the circuit breaker meets without difficulty in the static condition. Although the data plotted represents dielectric strength at the most critical interval after interruption, additional data previously mentioned indicate that the dielectric strength, while improving substantially a few cycles after interruption, remains below the rated BIL for several seconds. The flashover path is typically from the fixed contact of the upper break of the interrupter, out through the upper exhaust port and through the gas bubbles in the bulk oil to the tank. This path can be sparked over repeatedly in the Laboratory with no damage to insulation and with little evidence that it has happened.

Circuit Breaker Operation During Multiple Lightning

A. Typical Interruption With Multiple Lightning

In the typical case of a fault during a lightning storm, the first stroke initiates the fault by flashing over an insulator string of the transmission line to ground. An impulse wave travels from the fault through the closed breaker to the bus where a lightning arrester limits its voltage, or where parallel lines reduce the voltage by negative reflection. At this point there are no interruption gas bubbles in the oil so there is no flashover to tank in the circuit breaker.

Immediately thereafter, the relays sense the fault and the breakers on each end of the line are tripped and interrupt, creating gas bubbles in each break of the interrupters and in the bulk oil in the tanks. From instrumentation of expulsion protective gaps, it has been determined[2] that approximately twenty percent of lightning strokes are multiple-consisting of an average of 4 strokes spread over 10 cycles. Consequently, in a high percentage of cases the breakers will be subjected to lightning voltages during this critical period. Furthermore, as mentioned above, the line is open-ended at this time so any traveling wave tends to double by reflection and subjects the weakened breaker oil to a voltage that conceivably might be as high as twice the withstand of the line insulation, or more than twice the BIL of the breaker.

The fact that failure to interrupt, with resultant damage, does not occur in any significant number of cases is one of the most important pieces of data being considered. What actually happens, and can be reproduced in the Laboratory, is that a low energy sparkover occurs from the line side interrupter to tank, but there is no power frequency follow current. The only result is a minute mark on the tank wall similar to that placed on a sphere gap during Laboratory impulse testing. The path of the sparkover is through oil and exhaust gases, so it is self healing. The reason power current does not flow is that the initial lightning stroke shorts the transmission line, and then the breakers at both ends of the line open. Consequently the line side of the breaker does not supply power current.

A further factor is that the strengths inside the breaker must be properly coordinated. If some path from the line side through the breaker to the source side has the lowest dielectric strength, power fault current may be initiated in the breaker. If, on the other hand, the path from line side interrupter to ground has the lowest dielectric strength the impulse wave energy will be dissipated harmlessly in the self healing path through the oil. There would be no noticeable evidence that the flashover occurred. The writers have evidence that these harmless flashovers to tank occur many times each year in typical dead-tank oil circuit breakers. This internal coordination is an extremely important design principle which, if not incorporated in a circuit breaker, will surely result in a significant number of failures when interrupting lightning-initiated faults. Fig. 6 illustrates this principle in which the dielectric strength to tank (T) from interrupters (A) and (B), through the interrupter exhaust gases, must be less than that between the interrupters.

What would happen if dimensions were increased and the strength to tank were increased by some unknown means to more

than twice the BIL? The result would be power failures to interrupt unless the dielectric strength between bushings and along the normal arcing path were increased still more so as to prevent the overvoltage from creating a power fault from the bus side to the grounded line side bushing in the bulk oil in the tank.

The conclusion here is that proper coordination of relative insulation strength is much more important than the actual values, and increasing strength in one path to ground may actually create power failures that would otherwise be prevented by a voltage limiting action which drains the relatively small energy of a traveling impulse wave to ground.

This protective action of the internal circuit breaker gap is a detailed example of a general conclusion stated by Sporn and Gross[3], "The general principle of overinsulation, that is, adding insulation above past accepted standards has not proved very successful. Where it has been resorted to in the past and has not resulted in the mere transferring of the trouble to some other point in the system, it has invariably been at heavy economic expense."

B. Three Design Principles

At this point, three main design principles are self evident. The first involves the source side power voltages.

1. Dielectric strength from source side potential to ground must be sufficient to withstand power frequency and transient recovery voltages. Otherwise an internal power fault would appear, fed from the source to ground.

The second and third design principles are concerned with multiple lightning (or switching) voltages from the line side.

2. If a sparkover path to ground has a reasonable dielectric strength, making it self healing reduces drastically the chances of power failure or damage.

3. A self healing path which reduces dielectric strength from the line side potential to ground during interruption is often an essential part of successful interruption during multiple lightning. Such a shunting path should have a dielectric strength lower than any path through the breaker to the source side.

This third principle cannot always be maintained in practice for every instant during interruption. Furthermore, it can occasionally be violated without harm if flashover appears along the normal arcing path through the interrupters, if the interrupters are still able to function.

Factors Influencing Practical Impulse Voltages

Consideration will now be given to actual voltages that can occur at the breaker with a significant probability with the breaker in either the open or closed position and to the compounding of probabilities such that two or more rather unlikely situations must prevail simultaneously. For example, if the probability of occurrence of each of two events is one in 100 then the probability of both events occurring is only one in 10,000, and whereas the probability of occurrence of one event may in itself be significant, the probability of its occurrence while one or more other situations prevail simultaneously can be vanishingly small. This points up the need for considering all of the mitigating circumstances in arriving at design objectives for insulation coordination, even though the probability of failure due to any one of the circumstances is significant. Some of the factors for consideration in this respect are as follows:

A. Breaker Closed

With the circuit breaker closed, as it normally is for the first stroke of a multiple lightning discharge involving the line, there is no doubling by reflection at the breaker terminal. In fact, for the typical installation, the incoming wave is reduced by negative reflection at the lower surge impedance of the bus and is further protected by lightning arresters in the station. In the closed position, therefore, the insulation coordination characteristics need be only to a nominal value above the rated BIL.

B. Breaker Open

The probability of a normally applied breaker experiencing lightning voltage while open (thus permitting increases in voltage by reflection) is in the order of 1000 times greater in the several cycles following a fault interruption than it is when the breaker is standing open in the steady state condition without residual effects of recent fault interruptions. The reason is simply that multiple-stroke lightning occurs in roughly twenty percent of the cases so that a breaker on a line of say one outage per year would see once in every five years, on the average, the subsequent strokes of a multiple-stroke discharge after interruption of the fault initiated by the first stroke.

On the other hand the normally applied breaker will stand open on the line less than an estimated one hour a year so the chances of lightning striking this same line while the breaker is standing open during this time is the one hour divided by the number of hours in a year. This is in the order of once in 1000 to 10,000 years. Consequently, on a statistical basis, the only source of lightning voltage that need be considered with the breaker in the open position is that of multiple-stroke lightning during and immediately after interruption of the line fault associated with the initial stroke.

C. Ionized Gaps

Because the first stroke initiated a power fault that started the breaker operation, there is a path of hot, ionized gases out on the transmission line. This may tend to limit crest voltages on subsequent strokes. Furthermore, the dielectric strength from interrupter to tank along a self healing path will be below the BIL for many seconds. This will also limit the crest voltage actually seen by the breaker.

D. Effects of Corona on Wave Shape and Magnitude

Any stroke hitting a line conductor which is then flashed over to ground produces a traveling wave of very short duration. The reason is that the voltage exists only from the time of the initial stroke current to the time the short circuit to ground is established. This will take only a few tenths of a microsecond. A chopped wave of this type is attenuated very rapidly to the corona starting voltage of the line, typically in the order of one half of the breaker BIL connected to the line. On a 345 kv line, for example, this type of wave would be attenuated from 1300 kv to 500 or 600 kv in about 1000 feet. Upon reflection at an open breaker this wave will tend to double so that voltages approaching the BIL can be anticipated, but not significantly higher.

In the unlikely case in which the wave is not chopped, as for example a stroke of a multiple discharge hitting a line conductor but of insufficient voltage to flash over the ionized gases from the previous arc, corona exerts a less pronounced but nevertheless a mitigating influence on the severity of the voltage at the breaker terminals. This results from extraction of energy from the wavefront to establish the corona field with a resulting sloping of the wavefront. When the wavefront after reflection at the open breaker becomes greater than a few microseconds to crest,

a rod gap at the breaker will limit the voltage to approximately that of its critical flashover setting. Proper gaps would limit crest voltages to less than the BIL under this condition.

Finally, impulse tests on transmission lines[4] indicate that, because of the energy required to establish the corona field, the wave does not double at an open-line reflection. A more realistic value is the factor 1.6.

Summary of Effects of Lightning Voltages

1. The only significant opportunity for the normally applied breaker to experience lightning voltages which tend to double at the open breaker will result from multiple lightning during the clearing of a fault initiated by the first stroke.

2. During the interval of the multiple lightning, the internal dielectric strength from line interrupter to tank will be in the range from 50% to 100% of BIL in the typical dead-tank oil circuit breaker.

3. There are practically no cases of power failure or damage along this weakened path.

4. Because of the apparently very low possibility of trouble, the authors do not recommend that the static dielectric strength of an open circuit breaker be required to withstand hypothetical chopped wave voltages in the neighborhood of 200% BIL. Although some circuit breakers have passed such tests, the static dielectric strength above rated BIL is of little significance. Design margin would have to be reestablished above this higher requirement with considerable cost to the Industry.

Application of Principles to Air Blast Circuit Breakers

Fig. 7 shows a schematic sketch of one rating of a new design of air blast circuit breaker. The gas-filled current transformer is on the line side, although either side could be used.

Although data on dielectric strengths after interruption are very limited, the indications are that dielectric strength to ground will not drop as low as with oil breakers after interruption. The reason is that arced gases are cooled by screening and released in a region of very low electric stress. Furthermore, dielectric strength along the arcing path through the interrupters recovers quickly because the arced gases are removed almost instantly. However, just as with the oil circuit breakers, the authors believe that the most fruitful area of development is insulation coordination during interruption. It is believed that increasing static dielectric strengths, such as the self healing path at the throat of the gas-filled current transformer, would be ex-

pensive but would not yield value in reduced maintenance expense in service.

On what basis can one decide as to what the chopped wave strength or test voltage of the current transformer and the air blast breaker should be at, for example, 1 microsecond?

To be sure equipment will pass tests consistently the designers must include considerable safety factor. Thus a current transformer and air blast breaker designed to pass say a 650 kv BIL will on the average have a substantially higher dielectric strength. The actual strength for full wave impulse is then the BIL times the safety factor.

For the typical quasi uniform field of SF_6 insulation in the throat of a current transformer, the dielectric strength at 1 microsecond is (Fig. 8) roughly 30% higher than it is at 6 microseconds. Consequently, for a wave which reaches the open breaker, starts to double, and is chopped at 1 microsecond by a protective gap, the crest dielectric strength would be:

BIL x 1.3 x Safety Factor

Thus at no increased cost, and with the same safety factor, the breaker could pass a chopped wave test at 1 microsecond of 1.3 times the BIL. (Roughly, the same factor of 1.3 applies also to solid, oil impregnated insulation).

What would it mean in cost to increase this level to 2 times the BIL and maintain the same safety factor? This would simply mean increasing the internal BIL by the same factor: 2.0/1.3 or by about 50%. This would require large increases in spacings, greater cost of gas, higher pressures, etc. A very real and large improvement in performance would have to be demonstrated to justify such an increase. However, the authors believe there would be no recognizable reduction in field maintenance cost by increasing the dielectric strength of the self healing path in the air blast current transformer from, for example, 130% of BIL to 200% of BIL when the comparable self healing path in the oil circuit breaker has a strength well below the BIL during the time it is most likely to experience the highest lightning voltages.

CONCLUSIONS

1. Immediately after interruption, the dielectric strength between each interrupter and the tank wall of the typical oil circuit breaker drops far below its BIL (basic impulse level). A typical value is to 50% of the BIL. The reason is the low dielectric strength of gas bubbles which have been exhausted from the interrupters and which lie between the interrupters and the tank wall.

2. Three principles have been evolved for the design of breakers under these conditions. The first is the obvious one that the dielectric strength to ground must be sufficient to withstand power frequency and transient recovery voltage on the source side of the breaker. Otherwise a power fault would appear to ground inside the tank from the source side.

3. This first design principle can be met even at the highest currents now in use (66,000 amperes) by one of two methods:

   (A) Use lenticular tank with small air volume at top of oil;
   (B) Place closed cell rubber pads over an area of the tank wall that is much larger than the area of the oil-air interface at the top of the breaker. These procedures can increase dielectric strength to tank after interruption by 50% and more.

4. Another major consideration is the incidence of lightning voltages reaching an open breaker from the line side. For practical purposes it is only necessary to consider the case where the breaker is subjected to multiple lightning after the first stroke has caused a power arc on the transmission line. The average breaker is opening or stands open on the line such a small fraction of the year that the probability of an initial stroke occurring during that time is negligible.

5. There is a great deal of evidence that multiple lightning during interruption often causes harmless sparkovers from the line side interrupter to tank. Because the transmission line has been shorted by the initial lightning stroke (or has low dielectric strength through the recovering arc path), and because the breaker at the far end of the line has opened, there is no source of power current. This leads to the second design principle. If a sparkover path to ground has a reasonable dielectric strength, making it self healing reduces drastically the chances of power failure or of damage. The reason is that the system conditions which typically result in the highest impulse voltages also typically result in the absence or short circuiting of power frequency voltage.

6. The third design principle is that the dielectric strength to ground from the line side of the breaker should ideally be lower than the dielectric strength through the arcing path or through the breaker to the source side. If this can be maintained, a lightning surge from the faulted line will most probably be diverted harmlessly to ground through the self healing path and will not initiate the flow of power from the source.

7. At the present state of the art it is not possible to be certain of meeting this third principle at every instant during interruption. However, this principle can be violated as long as the sparkover path is along the normal current path through the interrupter and the interrupter is still able to function.

8. It should be emphasized that the question is not whether the tens of thousands of oil breakers in service can function adequately with the dielectric strength that has now been measured. That question is answered by the lack of power failures along the path from line interrupter to tank. The pertinent problem is rather to understand the principles that are operating to minimize trouble, and to avoid violating these principles in future design.

9. The air blast breaker, because of the efficient cooling of arced gases and because the gases are expelled so far from ground potential shows promise of having a smaller drop in dielectric strength after interruption than the conventional dead-tank oil circuit breaker. A further advantage is that the insulating paths under highest dielectric stress contain self healing gaseous insulation.

10. There is no known evidence that voltages as high as twice the BIL actually exist in any significant degree. Corona losses reduce the crest voltage of a traveling wave far below the theoretical value during its travel and reflection at an open breaker.

11. The authors conclude that the most fruitful area of development is during the interruption process when multiple impulse voltages are most likely to appear and when the dielectric strength may be 50% of the BIL. They do not feel the Industry would benefit by further increasing the static steep front dielectric strength which is probably already 130% of the BIL or higher. Coordination of dielectric strength of various self healing paths is concluded to be the key to economic progress for the Industry.

12. To advance understanding and to lead to the design of products with further reductions in the slight risk of trouble due to lightning, the new High Voltage Laboratory shown in Fig. 9 has been constructed to apply impulse voltages during power circuit interruption tests at the Development Laboratory.

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LIST OF CAPTIONS

Fig. 1 60-cycle dielectric strength of typical dead-tank oil circuit breaker shortly after interruption of short circuit currents.

Fig. 2 Typical pressure transient in the bulk oil in the tank of an oil circuit breaker.

Fig. 3 Construction of lenticular-tank 138 kv oil circuit breaker which utilizes the principle of limited air volume to provide adequate margin in dielectric strength to tank following interruption. Oil-level line is in bushing pockets.

Fig. 4 Plot of test data, all withstands, on dielectric strength after installation of pressure control pads. Dashed line of Fig. 1 superimposed for comparison of dielectric strength without pads.

Fig. 5 Estimated 3-microsecond chopped wave strength of typical oil circuit breaker shortly after interruption of short circuit currents. Test points derived from 60-cycle test data of Fig. 1.

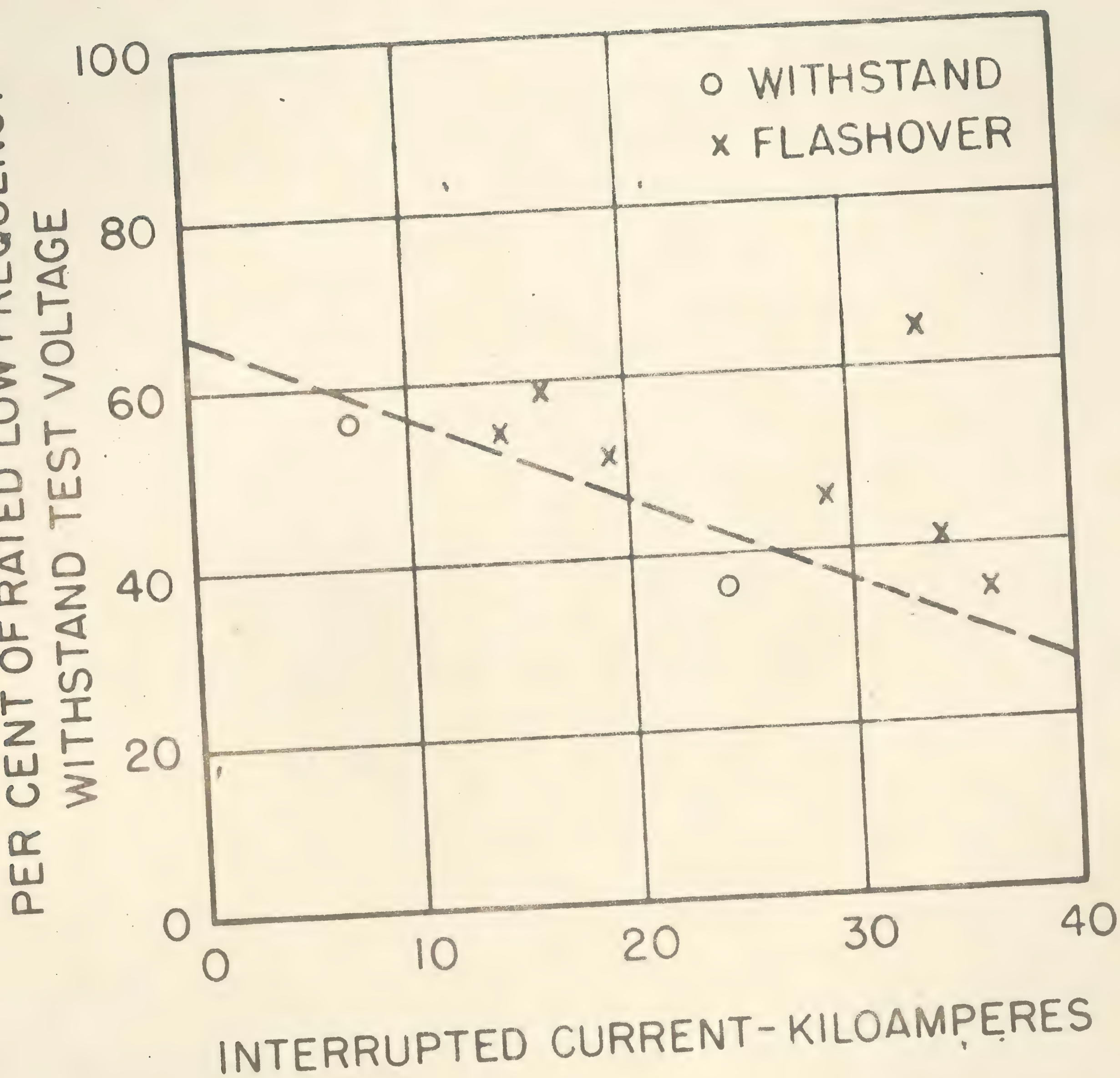
Fig. 6 Illustration of the principle of internal coordination of dielectric strength after interruption in oil circuit breakers that is necessary for performance adequacy in the presence of multiple lightning.

Fig. 7 Schematic sketch of one rating of a new design of air blast circuit breaker.

Fig. 8 Volt-time curve of a typical quasi uniform field representative of SF_6 insulation in the throat of a high voltage current transformer.

Fig. 9 New High Voltage Laboratory constructed adjacent to high power test facilities of the Development Laboratory for evaluation of multiple lightning performance of power circuit breakers during operation.

Fig 1



o WITHSTAND
x FLASHOVER
PER CENT OF RATED LOW FREQUENCY WITHSTAND TEST VOLTAGE
100
80
60
40
20
0
0
10
20
30
40
INTERRUPTED CURRENT-KILOAMPERES

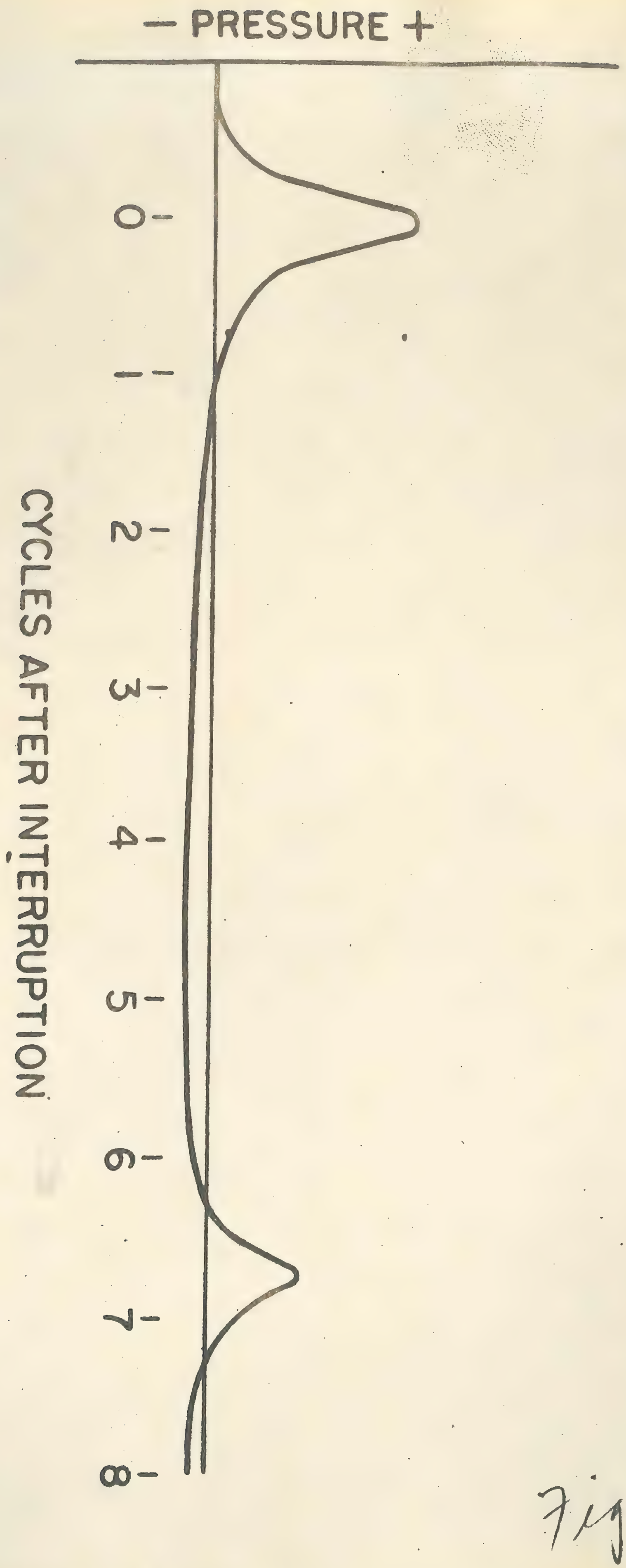
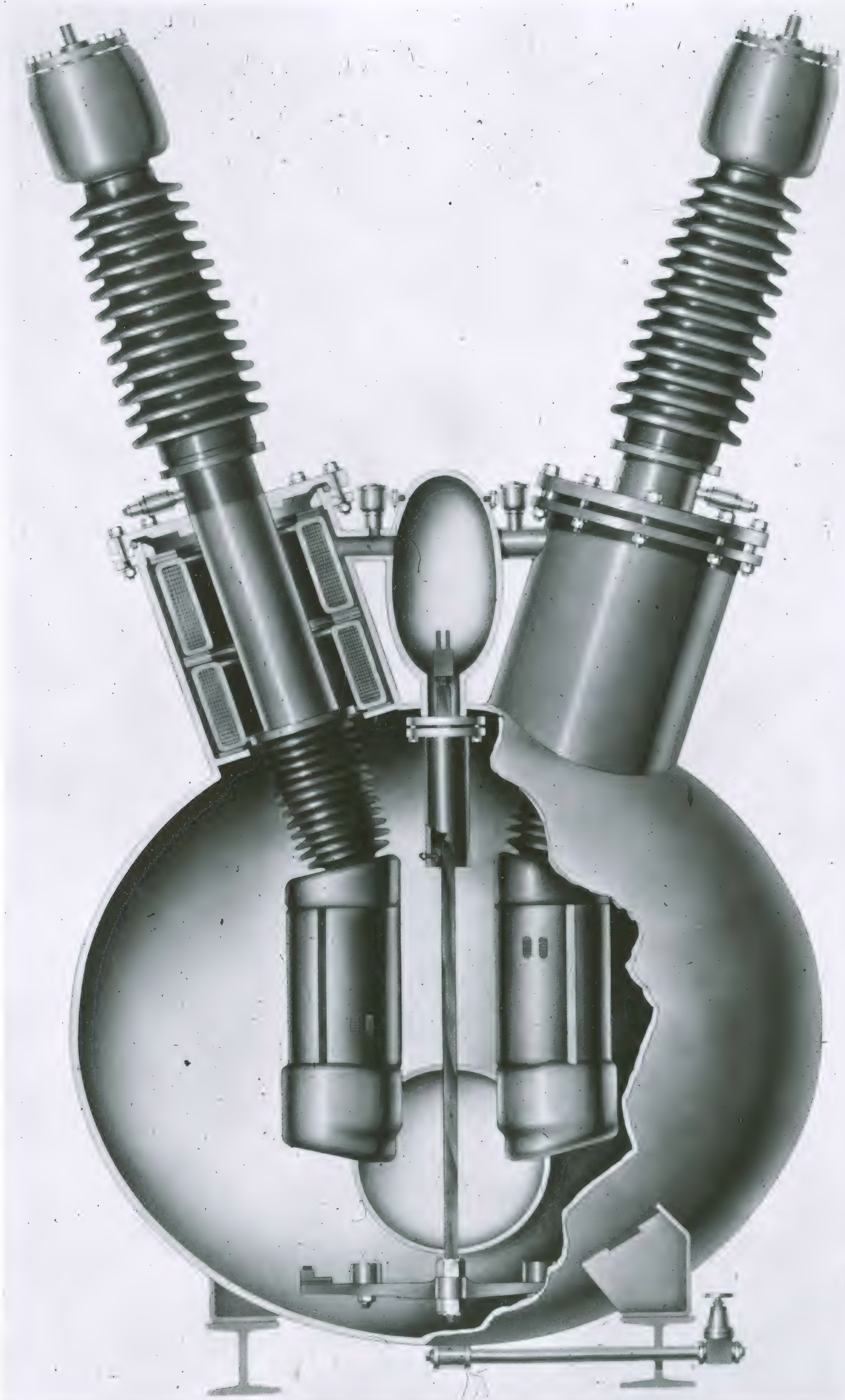


Fig. 2



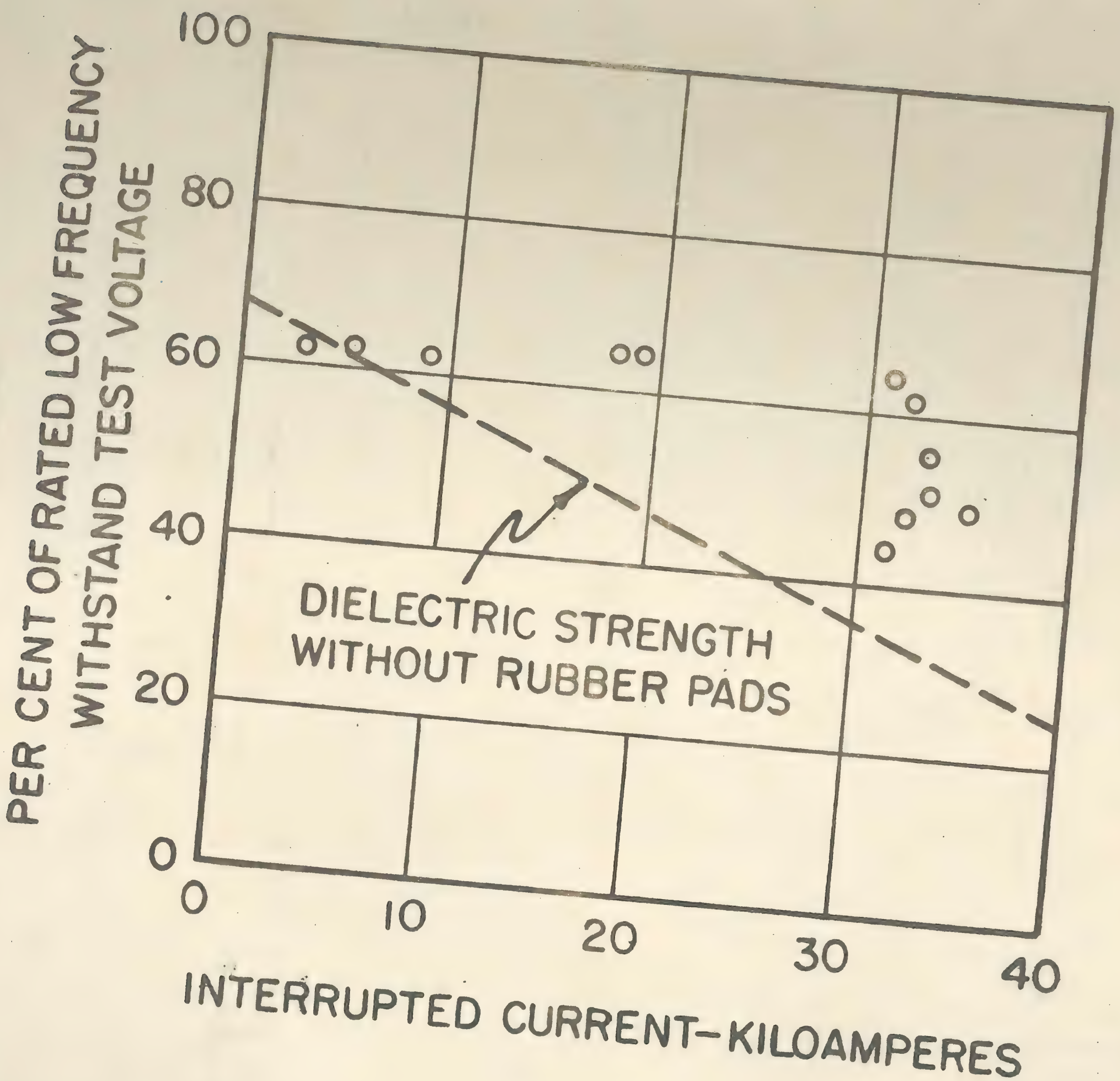

100
80
60
40
20
0
PER CENT OF RATED LOW FREQUENCY
WITHSTAND TEST VOLTAGE
DIELECTRIC STRENGTH
WITHOUT RUBBER PADS
0
10
20
30
40
INTERRUPTED CURRENT–KILOAMPERES

Fig. 4

r 4

Fig 5

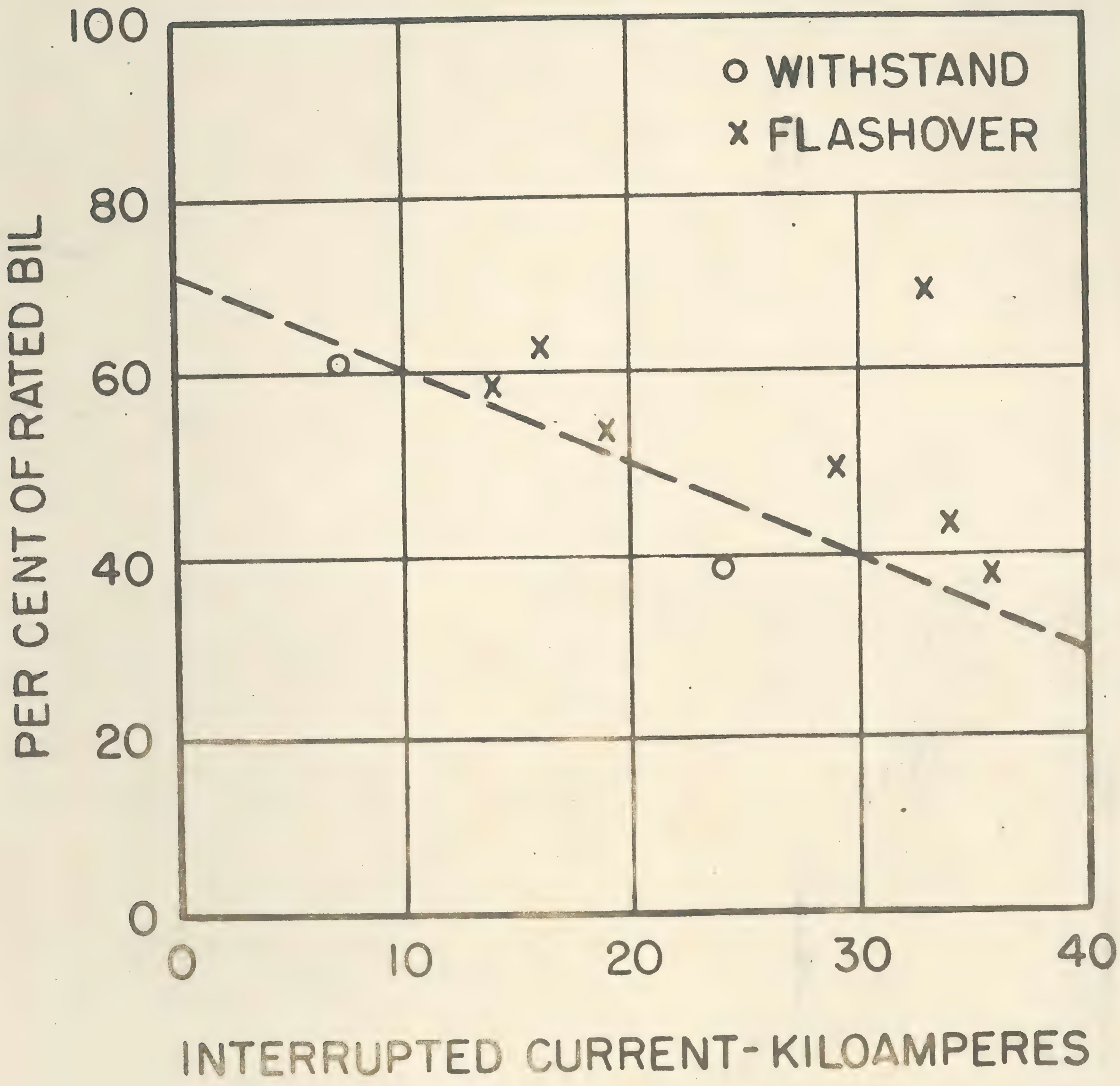

o WITHSTAND
x FLASHOVER
PER CENT OF RATED BIL
100
80
60
40
20
0
0
10
20
30
40
INTERRUPTED CURRENT-KILOAMPERES

Fig 5

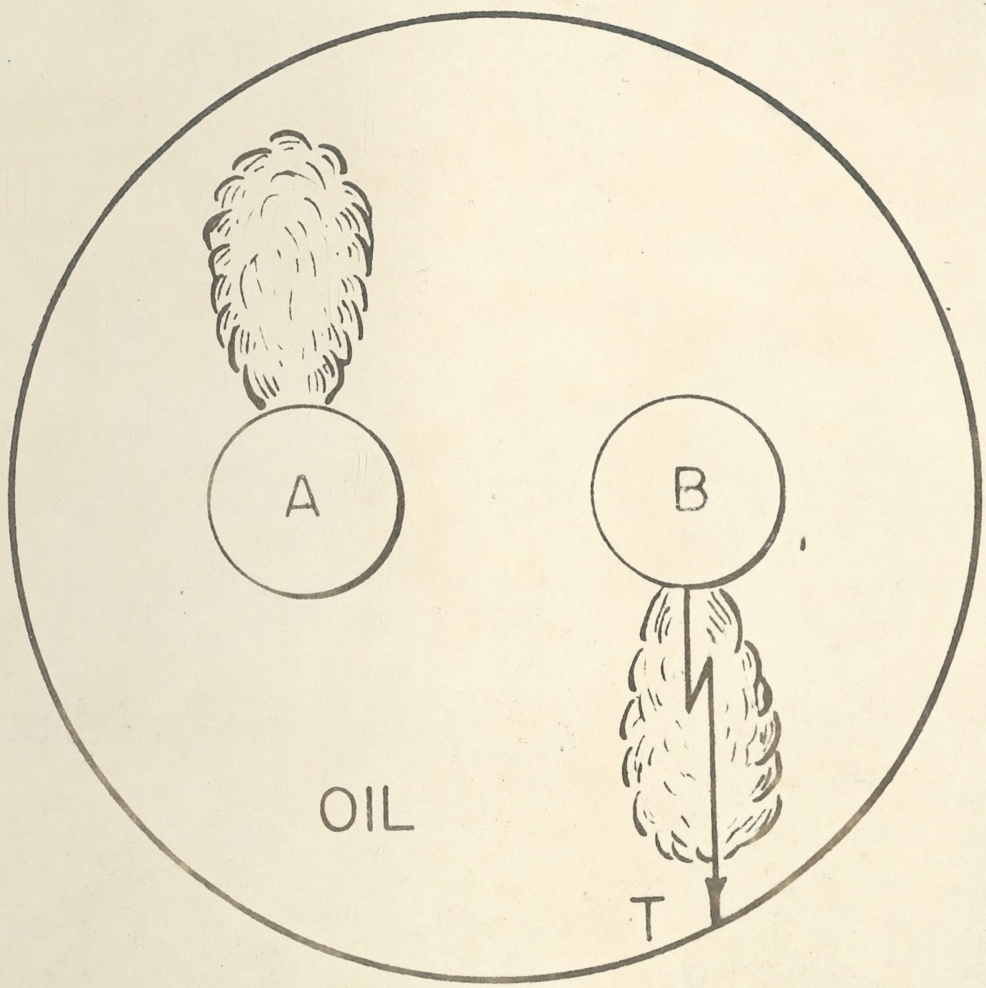
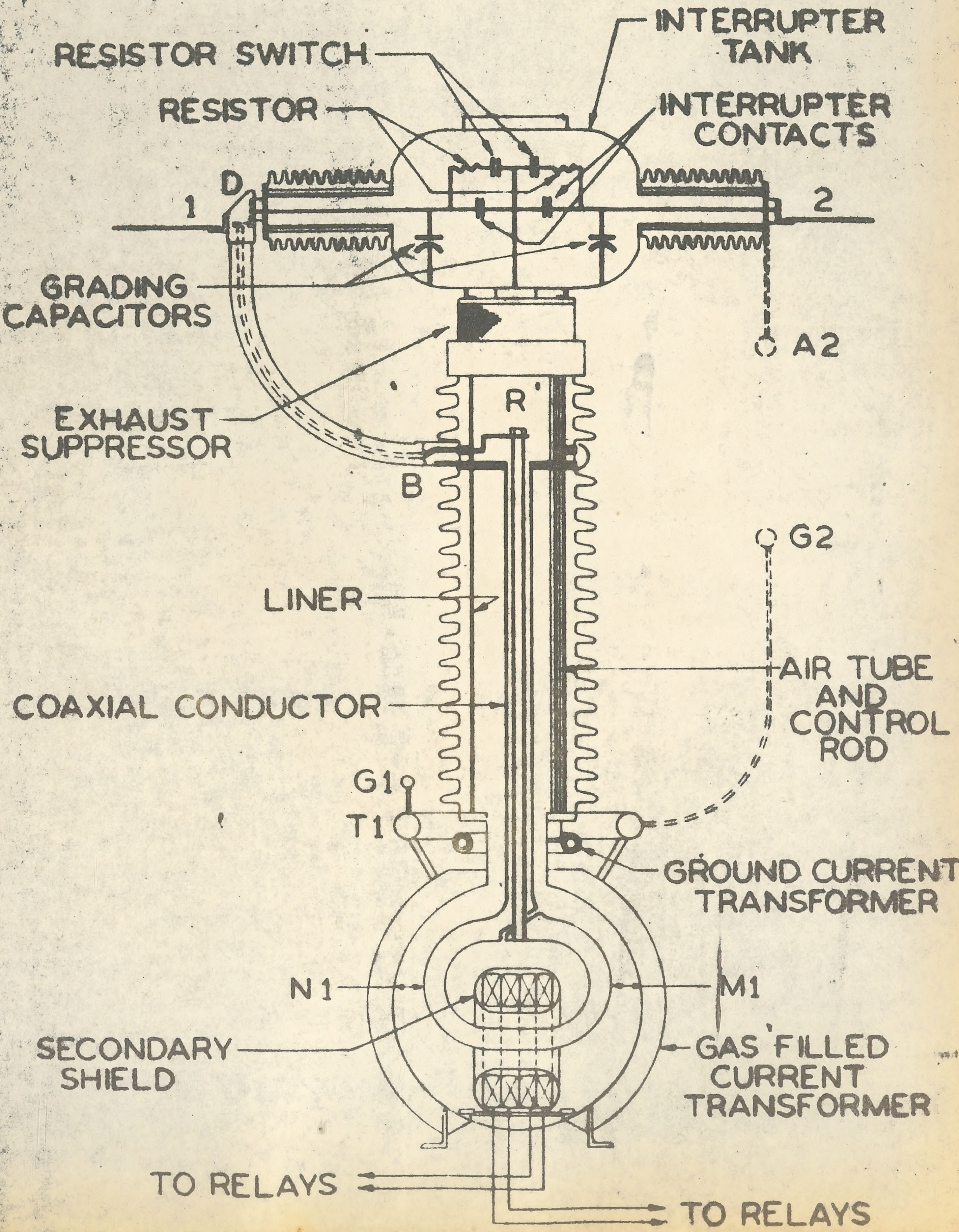


Fig 6

14

Fig 7


INTERRUPTER TANK
RESISTOR SWITCH
RESISTOR
INTERRUPTER CONTACTS
D
1
2
GRADING CAPACITORS
A2
EXHAUST SUPPRESSOR
R
B
G2
LINER
AIR TUBE AND CONTROL ROD
COAXIAL CONDUCTOR
G1
T1
GROUND CURRENT TRANSFORMER
N1
M1
SECONDARY SHIELD
GAS FILLED CURRENT TRANSFORMER
TO RELAYS
TO RELAYS

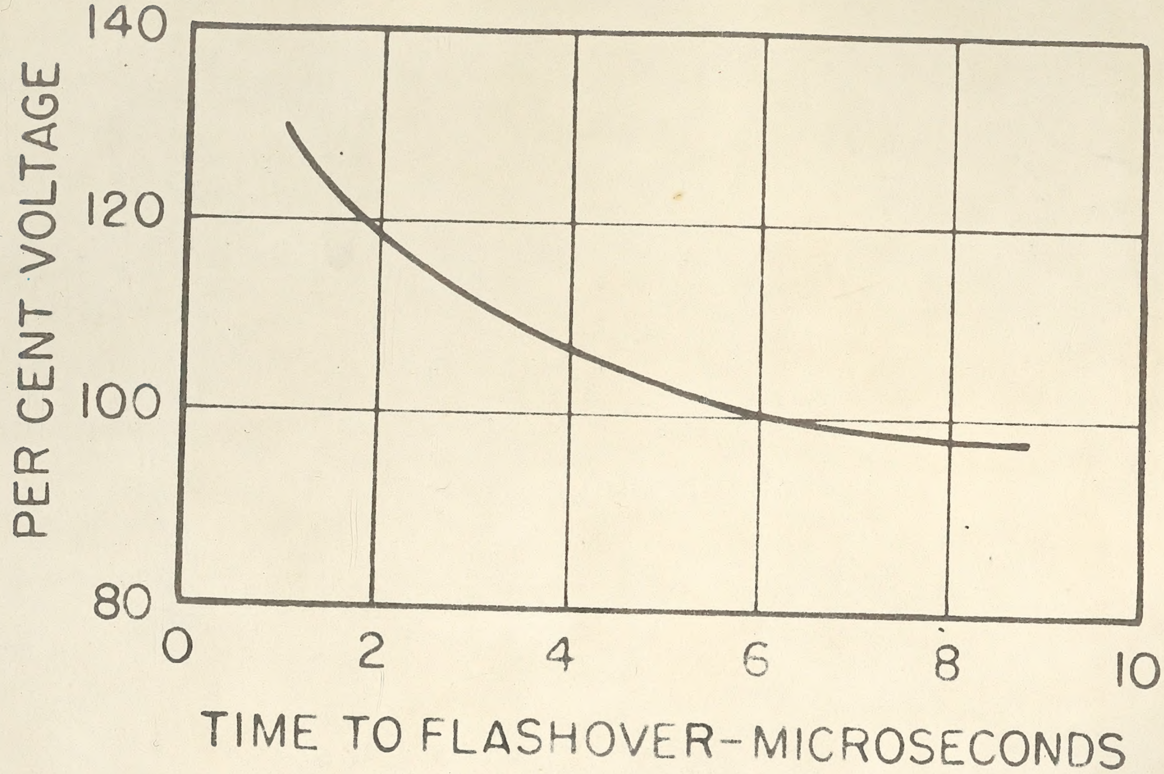

140
120
100
80
PER CENT VOLTAGE
0
2
4
6
8
10
TIME TO FLASHOVER-MICROSECONDS

Fig 8